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Motor Variability in Rowing

Maude Potvin-Gilbert
The University of Western Ontario

Supervisor
Nolte, Volker
The University of Western Ontario

Graduate Program in Kinesiology
A thesis submitted in partial fulfillment of the requirements for the degree in Master of Science
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Abstract

The aim of the study was to analyze the impact of environment, intensity and distance rowed on temporal variability of strokes and on knee angle variability. 11 participants rowed 2,000 m at high and low intensities on an ergometer and at high intensity in a single on-water. Data were collected at the beginning and at the end of each exercise. All the factors influenced significantly the temporal variability (respectively $\beta=-0.013$ and $p=.007$; $\beta=0.007$ and $p=.021$; $\beta=0.06$ and $p=.028$). The difference of visual information and the need of the rower to adapt to environmental factors might explain the greater temporal variability exhibited by the rowers while rowing on water. Participants exhibited a lower variability when rowing at high intensity which could be explained by increased difficulty of the task. Intensity and distance travelled did not influence significantly the variability of the knee angle on the ergometer.

Keywords

Rowing, Variability, Biomechanics

Co-Authorship Statement

Maude Potvin-Gilbert is the first author and Dr. Volker Nolte is co-author. All data in this thesis were collected, analyzed and interpreted by Maude Potvin-Gilbert.

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Chapter 1

1 Introduction

The World Rowing Federation, known as FISA (Fédération Internationale des Sociétés d’Aviron) was founded in 1892 and now includes 153 national rowing federations. Four years after FISA was established, rowing became an Olympic sport (World Rowing, n.d.-a). Nowadays, Olympic Games and World Championship, competitions are held on a 2,000 m course. Athletes need approximately five to nine minutes to cover the 2,000 m according to 2016 Olympic and World Championship results (World Rowing, n.d.-b) depending on their ability, the number of people in the boat, their gender and other external factors such as wind.

In rowing, athletes repeat the same movements over and over in order to be the first boat to cross the finish line. A full stroke cycle is divided into two phases which are called the “drive” and the “recovery”. The drive (propulsion phase) occurs between the catch (when the hands are closest to the stern of the boat) and the finish (when the hands are closest to the bow of the boat) positions. The recovery phase occurs between the finish and the catch positions (Thornton et al., 2017). These two phases are done in sequence in order to execute the stroke pattern. At the catch, rowers have their arms extended, their knees and their hips in flexion. While at the finish, athletes have their elbows in flexion, their knees extended and their hips greatly extended.

Rowers normally compete on water, but they can also compete indoors on an ergometer. Ergometers are often used as a substitute for on-water training when weather conditions are not adequate to row outdoors due to fog, low temperatures or high winds.

Rowers can row in singles, doubles, fours or eights. The number is associated with the number of rowers in the boat. Sometimes, there is also a coxswain in the boat. The role of the coxswain includes steering the boat, helping the rowers with the rhythm as well as their technique (Rowing Canada) .

Crew with similar force patterns are more efficient (Hill, 2002). When rowing in pairs, some rowers are able to adapt their force-time profile in order to increase their synchronicity with the other crew member (Baudouin & Hawkins, 2004). Seifert et al. (2017) determined that variability in the interpersonal coordination between rowers can be functional and allows the rowers to achieve a task-goal (related to the speed or the direction of the boat).

According to Srinivasan and Mathiassen (2012), motor variability addresses the differences between each movement and can be studied at different levels of movement execution across time within an individual. It can be measured using different types of variables, such as performance measures, kinetic variables, kinematic variables, muscle activity and coordination. Initially, variability in motor function was considered dysfunctional and harmful to performance. Intra-individual variability was considered to be noise in the motor system (Srinivasan & Mathiassen, 2012). However, recent research shows that variability occurs at different expertise levels and can sometimes be considered functional. The role that variability plays in the coordination and control of the sensorimotor system is a central issue for motor control studies (Newell & Corcos, 1993).

A few studies report that motor variability and performance can be described in a “U-shaped” relationship. Novices who are learning to do a skill have lots of variability in their patterns while sub-elites have only little. Experts have more variability than sub-elites which allows them to spread the load of training or competition across different body structures by developing more variable motor strategies. Variability exhibits by experts is functional in opposition to variability exhibits by novices (Bartlett, Wheat, & Robins, 2007; Srinivasan & Mathiassen, 2012). Also, experts can use movement variability in order to adapt to different situations (Bartlett et al., 2007).

1.1 Purpose and Hypotheses

1.1.1 Purpose

While some studies present benefits about motor variability (Bartlett et al., 2007), these benefits are not as clear in rowing literature. While rowing literature considers

consistency important for performance, it would be interesting to see if the benefits of variability outlined in motor variability literature apply to rowing. It would also be interesting to see how different factors affecting motor variability presented in the literature influence motor variability while rowing. Using motor variability in order to study rowing might allow researchers to better understand the rowing motion.

The purpose of this study is to evaluate the impact of different factors on motor variability. Spatial (variability in joint angle) as well as temporal variability (stroke duration variability) will be used to analyze motor variability in rowing.

The different factors that will be studied are:

- Environment (on-water rowing and ergometer rowing)
- Intensity (low intensity and high intensity)
- Distance rowed (beginning of the exercise and end of the exercise)

1.1.2 Hypotheses

- Environment will influence temporal variability of strokes
- Intensity will influence temporal variability as well as knee joint angle variability of the rower's movements.
- Distance rowed will influence temporal variability as well as knee joint angle variability of the rower's movements.

Chapter 2

2 Literature review

This chapter will present an overview of the literature linked to motor variability and rowing.

2.1 Variability of Different Systems in the Body

According to Newell and Corcos (1993), variability is inherent within and between all biological systems. Heart rate variability (HRV), variability in the electrical signals of the brain and motor variability are examples of variability that have been studied in different systems of the human body. Variation in biological processes might be explained by health or diseases (James, 2004).

HRV has not only been studied in sick and injured people but also in athletes. HRV represents adaptive responses of the autonomic nervous system to challenges to the circulation that can be seen for example with respiration (Malik, 1998). Low HRV is associated with a higher risk of myocardial infarction and neuropathic diabetes (Malik, 1998). In middle aged men (40 to 60 years old) participants who were classified in the low heart rate variability group had higher systolic blood pressure, higher heart rate, and were more likely to die from various causes (Dekker et al., 1997). In addition, it seems that there is evidence of reduced HRV during low intensity and steady state exercise up to 10 days following a concussion (Blake, McKay, Meeuwisse, & Emery, 2016).

For athletes, HRV is studied in relation to fatigue. Kajaia, Maskhulia, Chelidze, Akhalkatsi, and Kakhabrishvili (2017) concluded that the cardiac autonomic imbalance observed in over-trained athletes implies changes in the variability of the heart rate signal, and therefore HRV could provide valuable information in the detection of overtraining in athletes. Similarly, results from a case study by Plews, Laursen, Kilding, and Buchheit (2012) suggests that HRV may be a useful measurement indicative of the progression towards non-functional overreaching. Non-functional overreaching can be described as a stress-regeneration imbalance with negative outcomes. HRV has also been

studied as a way to monitor the training load in rowing (Plews, Laursen, Kilding, & Buchheit, 2014). To summarize, HRV had been widely used in order to get information about the health of different populations.

The electroencephalogram (EEG) records the electrical activity of the brain and the electric signals have been analyzed using a method of nonlinear dynamics in order to measure chaos in those signals. Stam et al. (1994) demonstrated a decrease in chaotic dynamics in the EEG signals of demented and Parkinson Disease patients. In addition, the link between EEG signals and epilepsy have been studied, in that, during an epileptic seizure of short duration, the brain activity signal tends to have a more stable periodic motion. Furthermore, Gallez and Babloyantz (1991) studied brain activity in three different stages: alpha waves (eyes closed), deep sleep (stage four) and the Creutzfeld-Jakob coma. They found that the degree of chaos in the EEG signal increases from a coma to a deep sleep and from a deep sleep to an awake stage. A higher chaotic level in the EEG signals may lead to a wider variety of responses and behaviours (Gallez & Babloyantz, 1991). In contrast, information processing would be impossible given stable periodic motion in the EEG signals (Babloyantz & Destexhe, 1986). It could be explained by the chaotic dynamics increasing the resonance capacity of the brain. According to the previous studies, having more chaotic brain electrical activity may be an indicator of good health.

The relation between motor variability and various health problems has also been studied. Perturbations to the normal state of a human's system (e.g., pain and fatigue) might cause adaptations in movement variability (Lomond & Côté, 2010) and may have important clinical implications too (Madeleine, Mathiassen, & Arendt-Nielsen, 2008). Variability in the motor system can either increase or decrease with distress. For example, elderly fallers showed two-fold greater variability than elderly non-fallers for the first step length during their gait initiation patterns. Mbourou, Lajoie, and Teasdale (2003) concluded that this variability might be a predictor of postural problems. On the other side, Hamill, van Emmerik, Heiderscheit, and Li (1999) observed decreased variability of the continuous relative phase which is a measure of coordination patterns in symptomatic individuals with patellofemoral pain compared with non-injured individuals.

Motor variability can either be beneficial or detrimental to performance depending on the parameter of interest (Heiderscheit, Hamill, & van Emmerik, 2002). A lack of variability is associated with a system that has too much rigidity and is unable to adapt to stresses (Georgoulis, Moraiti, Ristanis, & Stergiou, 2006) and any excess of variability is associated with a system that is noisy and unstable (Stergiou, Harbourne, & Cavanaugh, 2006). In other words, any lack or excess of variability can be associated with abnormal motor development or unhealthy states (Stergiou et al., 2006).

Variability in the human body can be used to distinguish healthy and diseased systems. The study of variability in biological rhythms has provided researchers with extremely useful insights for their understanding of pathology (Georgoulis et al., 2006). It is important to note that the optimal amount of variability depends on the biological system involved and the variable under examination (James, 2004).

2.2 Influence of Fatigue on Motor Variability

Fatigue does not have a widely accepted definition according to Friedman and Friedman (1993). Enoka and Stuart (1985), for example, defined it as a “progressive increase in the effort required to exert a desired force and the eventual progressive inability to maintain this force in sustained or repeated contractions” (p.2281). Moreover, Cortes, Onate, and Morrison (2014) suggest that the impact of exercise-induced fatigue is not only restricted to a decline in the force producing capacity of the system, but is also related to the variability of the movement pattern. Likewise, the relationship between fatigue and motor variability has been studied by some other researchers (Cignetti, Schena, & Rouard, 2009; Cortes et al., 2014; Fuller, Fung, & Côté, 2011; Selen, Beek, & van Dieën, 2007).

Qin, Lin, Faber, Buchholz, and Xu (2014) studied kinematic variability in simulated light assembly work. Participants had to use their dominant hand in order to reach for and pick up washers and stacked them during four sessions of 20 minutes each. The researchers observed decreased variability in the wrist and the elbow flexion over time, but an increase in the variability of the shoulder abduction and the wrist radial deviation. These adaptations may have occurred to reduce the load on the fatigued shoulder, and to compensate for the development of fatigue. Qin et al. (2014) suspected that these changes

in variability over time occurred in order to fulfill specific task requirements. Moreover, Hellard et al. (2008) studied motor variability with regards to fatigue in swimming. They found decreased stroke rate variability during the second 100 m of a 200 m race for backstroke, butterfly and freestyle races in comparison to the first 100 m of each race which might be explained by a fatigue effect.

Srinivasan and Mathiassen (2012) suggested that more motor variability might lead to a slower development of fatigue and relieve the load on fatiguing tissues. Gates and Dingwell (2011) have shown that motor variability increases with fatigue in a task similar to sawing. In this study, the authors suggest that the increase in variability is possibly due to adaptations that the subjects made to combat fatigue or might directly be associated with neuromuscular fatigue. Other studies have reached the same conclusion for different tasks such as cross-country skiing (Cignetti et al., 2009), tracking a target with elbow flexion and extension (Selen et al., 2007), and a repetitive reaching task (Fuller et al., 2011). Selen et al. (2007) concluded that, even if fatigue did not affect the success of the reaching task or the flexion and extension of the elbow task, fatigue had an impact on motor variability during the movement.

Aune, Ingvaldsen, and Ettema (2008) compared the change of motor variability in expert and recreational table tennis players during a prefatigued and fatigued condition. Table tennis players showed a reduction in power-generation capacity between 28% and 39% when in a fatigued condition compared to a prefatigued condition. Highly skilled players had a high variability of the movement patterns for all segments (shoulder, elbow, wrist, and racket) during the prefatigued condition, while the variability was smaller in the fatigued condition. Recreational table tennis players had a lower variability of the movement patterns for all segments during the prefatigued condition. For the fatigued condition, the variability remained relatively stable or increased depending on the segment studied.

Studies have shown that motor variability can be affected negatively or positively by fatigue. According to Srinivasan and Mathiassen (2012), the difference in effect of

fatigue on motor variability might be task specific or due to individual capacity such as skill level (Aune et al., 2008).

2.3 Influence of Fatigue in Rowing

Rowing is classified as an endurance sport. In fact, rowers are repeating the same movement patterns. Studies have shown that some physiological, as well as some biomechanical, changes take place as a result of this prolonged type of movement.

Holt, Bull, Cashman, and McGregor (2003) studied kinematical changes in the spine during a rowing exercise that lasted for one hour. They observed an increase of the maximal flexion of the spine which might be attributed to muscle fatigue in this area. Holt et al. (2003) suggested that this change may even have an impact on low back pain. Mackenzie, Bull, and McGregor (2008) were also interested in the same topic, but found no kinematical changes (spine, thigh flexion/extension, relative timing during the stroke where maximal thigh flexion/extension occurs, femoral extension at the finish, maximal femoral extension as well as the relative timing during the stroke where maximal femoral extension occurs). They explained the difference between the results of their study and those of Holt et al. (2003) by the divergence between the athletes' familiarity and experience with the test performed. Athletes were more familiar with the test performed in Mackenzie et al. (2008).

Wilson, Simms, Gormley, and Gissane (2011) were interested in comparing the lumbar spine kinematic during a fatiguing protocol of ergometer and on-water rowing. They found a significant increase in the range of motion of the lumbar spine on the ergometer compared to on-water rowing.

Pollock, Jones, Jenkyn, Ivanova, and Garland (2012) used electromyography and kinematics to quantify fatigue in a 2,000 m simulation race on a Concept2[®] rowing ergometer. They found a change in the sequencing of the legs, trunk and arms, since the peak angular velocity of trunk extension and upper extremity flexion occurred later in the drive at 1,500 m compared to at 250 m. This could be due to the trunk becoming more flexible which might lead the trunk to be less able to transfer forces from arms and legs.

Husmann et al. (2017) found a significant decrease of isometric and concentric maximal voluntary contraction of the knee extensors for both females and males following a 2,000 m rowing exercise. The researchers attributed the knee extensor strength loss to central fatigue since there were no significant changes for the quadriceps twitch torque in response to paired electric stimuli which are associated with peripheral fatigue.

Frias et al. (2018) studied the impact of rowing a very long distance (160 km) on different biomarkers. The concentration of biomarkers related to inflammation (including Il-6 and TNF alpha) and cardiac activity (creatinine kinase and pro brain natriuretic peptide (NT-proBNP)) increased between pre and post exercise. Post-exercise, their lipid profile was better since there was a decrease of triglycerides and total cholesterol and an increased in high-density lipoprotein cholesterol (HDL-c).

To conclude, most studies have found kinematical changes as well as hormonal changes with rowing exercises. These changes are a sign of fatigue in rowing and may result in decreased performance, as well as an increased risk of injuries.

2.4 Influence of Injuries on Motor Variability

Studies have shown that pain and injuries may affect motor variability (Côté, Raymond, Mathieu, Feldman, & Levin, 2005; Georgoulis et al., 2006; Lamothe, Meijer, Daffertshofer, Wuisman, & Beek, 2006; Madeleine et al., 2008; van den Hoorn, Bruijn, Meijer, Hodges, & van Dieën, 2012). The nature of the pain itself (Madeleine et al., 2008) and the patient's perception of it (Moseley & Hodges, 2006) might be factors that influence movement variability.

The variability of task timing increased during experimentally induced pain compared to before the pain induction and the authors hypothesized that increased variability during acute pain might be the central nervous system's way of finding the least painful solution for each task (Madeleine et al., 2008). Moseley and Hodges (2006) introduced a painful stimulus to their study's participants. Participants were classified into two groups. Participants for whom the timing of abdominal muscle activation in the last 10 no-pain trials was no different than in the last 10 pain trials were classified as nonresolvers. The

remaining participants were classified as resolvers. Resolvers had a greater variability for the last 10 pain trials as well as the remaining no pain trial compared to nonresolvers. It seems that the resolvers were able to adapt to the pain stimulus compared to the nonresolvers. Interestingly, nonresolvers were characterized as those believing they suffered from back trouble. Moseley and Hodges (2006) suggested that the loss of variability might be associated with these participants' perception of lingering back pain.

For butchers with chronic neck-shoulder pain who performed a simulated meat cutting task, kinematic variability (arm and trunk accelerations) decreased compared to healthy individuals (Madeleine et al., 2008). Another study from Madeleine and Madsen (2009) reported a decrease of motor variability at the head-shoulder vertical displacement joint for individuals with discomfort in the neck shoulder region. The discomfort also affected the variability in remote locations such as elbow or hip joints. van den Hoorn et al. (2012) found that participants with chronic low back pain adopted a more protective movement, and so increased trunk stiffness. In the same vein, Moseley and Hodges (2006) demonstrated that participants with reduced variability after induced back pain failed to return to a normal postural strategy when the pain stopped. Madeleine et al. (2008) explained this decrease due to the motor system becoming less flexible due to chronic pain. The non resolution of the normal variability following a chronic pain episode might increase the risk of further back pain (Moseley & Hodges, 2006).

Similarly, Georgoulis et al. (2006) found that variability of the flexion-extension of the knee decreased on the injured knee compared to the contralateral knee for participants with ACL injury. This decrease might lead to a greater likelihood for future injuries at the knee because patients are unable to adapt to changing environmental demands (Georgoulis et al., 2006). Hamill et al. (1999) suggested that the variability has a functional role in the coordination of the lower limbs. The researchers saw a decrease in the variability of the thigh rotation and leg rotation coupling for the injured limb of the patellofemoral pain group compared to the healthy one. They could not determine if pain was a cause or a consequence of motor variability. Moreover, Gallagher, Nelson-Wong, and Callaghan (2011) studied the variability of the position of the centre of pressure during prolonged standing with patients with chronic low back pain. They concluded that

decreased variability is an adaptive response to the pain as opposed to a consequence of it.

According to Bartlett et al. (2007), Hamill et al. (1999) and Srinivasan and Mathiassen (2012), increased motor variability would divide stresses among different tissues and would decrease the load on a specific tissue. Even after recovery, reduction of motor variability can persist (Moseley & Hodges, 2006; Sterling, Jull, & Wright, 2001) and might increase the chance of getting successive injuries (Georgoulis et al., 2006; Moseley & Hodges, 2006).

To summarize, pain could be a cause and/or a consequence of motor variability. Chronic pain reduces motor variability at the injured site to minimize pain while acute pain may increase motor variability in order to find the least painful pattern (Srinivasan & Mathiassen, 2012). The diminution of motor variability might stay after recovery even if the pain is gone and increases the risk of further injuries by preventing adaptation.

2.5 Rowing Injuries

The vast majority of injuries in rowing are overuse injuries (Hosea & Hannafin, 2012; Rachnavy, 2012; Smoljanovic et al., 2015), and caused by the repetitive nature of the sport. Essentially, different body parts are particularly stressed because of the intensity and the vast number of repetitions of the rowing motion (Hosea & Hannafin, 2012). According to Smoljanovic et al. (2015), the mean injury rate per year is 0.92 injuries per rower which represents 1.75 injuries per 1,000 training sessions per rower. Injury incidence is proportionally related to the volume of training and technique (Hosea & Hannafin, 2012). It can also be linked with poor technique, fatigue, overload, rapid changes in training frequency, intensity or volume (Rachnavy, 2012; Rumball, Lebrun, Di Ciacca, & Orlando, 2005; Thornton et al., 2017). Changing boat classes like going from a bigger boat to a smaller boat, changing from sweep to sculling or vice versa are factors that are associated with injuries too (Evans & Redgrave, 2016b). The two most common sites of injury are the lower back and the knee (Evans & Redgrave, 2016b).

2.5.1 Lower Back

The lower back is the most reported injury site in rowers (Rumball et al., 2005; Wilson, Gissane, & McGregor, 2014). The incidence of lower back injury is between 1.5 and 3.7/1000 h of rowing and associated training (Thornton et al., 2017). Adolescent rowers have reported greater low back pain prevalence compared to the general population (Ng, Perich, Burnett, Campbell, & O'Sullivan, 2014). Low back pain can even bother athletes during activities of daily living (ADL) as reported by Maselli et al. (2015). They reported that 40% of the athletes that filled out a questionnaire about pain reported some limitations in their ADLs during their last episode of low back pain. Low back pain is most likely to develop in the winter months compared to the other seasons (Wilson et al., 2014). Factors that are significantly associated with the development of low back pain are age at the time of the survey, history of rowing before age 16, use of larger blade surfaces like a hatchet blade oar, training with free weights, weight machines and ergometers, and ergometer training sessions lasting longer than 30 minutes (Thornton et al., 2017; Wilson et al., 2014). The main causes of low back injuries are hyperflexion and twisting (Rumball et al., 2005). Also, excessive use of lumbar flexion and extension without accompanying pelvic tilting may lead to increased lumbar spine loading (Wilson et al., 2014), which may cause low back pain. Similarly, adolescent rowers reported that ergometer rowing, long rowing sessions and sweep rowing are factors that increase pain intensity. Spondylosis, sacroiliac joint dysfunction and disc herniation are examples of low back injuries in rowing (Rumball et al., 2005). Treatment for low back pain include strengthening exercises, physiotherapy, and rest (Rumball et al., 2005; Thornton et al., 2017).

2.5.2 Knee

Knee injuries are also considered common in rowing. Knee injuries represented 15.91% of total injuries (Wilson, Gissane, Gormley, & Simms, 2008). The rowing motion requires the knee to move through its full range of motion (Thornton et al., 2017). Some knee injuries might be due to the repetition of the flexion and extension motion under load (Hosea & Hannafin, 2012). In addition, Rachnavy (2012) found a significant difference in the kinematic of the knee angle between injured and healthy athletes in

rowing, a difference that appears to be related to rowing injury. Patellofemoral pain syndrome, tendinopathy, and iliotibial band friction syndrome are some examples of knee injuries in rowing (Rumball et al., 2005; Thornton et al., 2017). Treatment for knee injuries includes nonsteroidal anti-inflammatory medication, stretching programs, physiotherapy, ice and rest but can also contain local corticosteroid injection (Hosea & Hannafin, 2012; Thornton et al., 2017).

2.5.3 Upper Limb

Upper limbs are the third most frequently injured site in rowing (Hosea & Hannafin, 2012). Upper limb injuries represent approximately 14% of the total number of injuries for the rowing programs at Harvard and Rutgers universities. Examples of upper limb injuries include shoulder pain, lateral epicondylitis, deQuervain's tenosynovitis, exertional compartment syndrome, and intersection syndrome (Hosea & Hannafin, 2012; Rumball et al., 2005). Shoulder pain can be due to overuse, poor technique or tension in the upper body (Rumball et al., 2005) while poor technique or fatigue can cause forearm and wrist injuries (Thornton et al., 2017). Treatments for upper limb injuries include ice, stretching, massage, relative rest, acupuncture as well as nonsteroidal anti-inflammatory medication and cortisone injection (Hosea & Hannafin, 2012; Thornton et al., 2017).

2.5.4 Rib

Rib cage pain is common in the rowing population (Hosea & Hannafin, 2012), and can be attributed to rib stress fractures (RSFs), costochondritis, costovertebral subluxation, or intercostal muscle strains (Hosea & Hannafin, 2012; Rumball et al., 2005). RSB has an average incidence of 9.1% in rowing (McDonnell, Hume, & Nolte, 2011). Of these, RSFs account for the most time lost from on-water training and competition (Rumball et al., 2005). Hooper, Blanch, and Sternfeldt (2011) reported that an average of two months of training is lost due to rib stress fractures. RSFs are one of the least understood of all rowing injuries (Vinther & Thornton, 2016). Even though the mechanism of injury is unclear (Evans & Redgrave, 2016b), some researchers have suggested that the co-contraction of some thoracic muscles, such as serratus anterior and the external oblique muscles, might be one of the causes (Evans & Redgrave, 2016b; Hosea & Hannafin,

2012; Karlson, 1998). Multiple risk factors of RSFs have been identified by Evans and Redgrave (2016a). Intrinsic factors include previous rib injury, relative energy deficiency in sport, poor trunk strength/ endurance/ mobility/ flexibility, as well as other types of injuries. Examples of extrinsic factors associated with RSFs are changes in training environment such as big boat to small boat, sweep rowing to scull or vice versa, as well as increased training load, volume and intensity. The Great Britain Rowing Team guidelines suggest managing rib injuries by decreasing the load on the rib by stopping rowing activities. Three to six weeks of recovery is the recommended healing period. A progressive return to rowing is also suggested (Evans & Redgrave, 2016a, 2016b).

2.5.5 Other Injuries

Other injuries and health problems have been reported in the rowing literature, such as female triad, dehydration, and dermatological issues including blisters and abrasions (Rumball et al., 2005; Thornton et al., 2017). Also, some health issues can be associated with a specific rowing population. Eating disorders as well as energy availability can be an issue especially for lightweight rowers (Beggs, Nolte, & Dickey, 2016; Thornton et al., 2017) while pressure sores can be a problem for para-rowers (Thornton et al., 2017).

In summary, most rowing injuries can be associated to overuse (Hosea & Hannafin, 2012; Rachnavy, 2012; Smoljanovic et al., 2015) and can occur in various parts of the rower's body. An appropriate loading in the boat (choosing the right oar) or on the ergometer (choosing the right resistance) can reduce risk of overuse injuries (Thornton et al., 2017). Well-designed prospective studies are still needed in order to identify risk factors for injuries (Thornton et al., 2017; Vinther & Thornton, 2016) and low back pain (Maselli et al., 2015), which will help coaches, athletes and therapists to prevent pain and injuries that might affect ADLs (Maselli et al., 2015) or even informing premature ends to athletic careers (Vinther & Thornton, 2016).

2.6 Comparisons of on-Water Rowing and Ergometer Rowing

Rowing is a sport that is greatly impacted by environmental factors, such as wind, rain, waves and temperature (de Campos Mello, de Moraes Bertuzzi, Grangeiro, & Franchini,

2009; Elliott, Lyttle, & Birkett, 2002; Mikulić, Smoljanović, Bojanić, Hannafin, & Matković, 2009). In order to avoid these environmental factors, rowers sometimes train on ergometers, which are also often used in order to assist crew selections as well as to conduct physiological testing in a more controlled environment (Bazzucchi et al., 2013; de Campos Mello et al., 2009; Elliott et al., 2002; Fleming, Donne, & Mahony, 2014; Lamb, 1989; Mäestu, Jürimäe, & Jürimäe, 2005; Martindale & Robertson, 1984). Of the different types of rowing ergometers, the most popular is the air-braked stationary ergometer of Concept2[®] (Fleming et al., 2014; Kleshnev, 2008). Also, dynamic ergometers, such as the Rowperfect[®] ergometer, have been studied and are supposedly designed to simulate the force transfer of on-water rowing more accurately (Fleming et al., 2014; Mäestu et al., 2005). While comparing dynamic versus stationary ergometers, Benson, Abendroth, King, and Swensen (2011) concluded that the force profile as well as the high stroke rates on dynamic ergometers are more similar to on-water rowing compared to static ergometers.

2.6.1 Kinematic and Kinetic

Concerning the kinematics of a rowing stroke, Lamb (1989) found that the movements of the upper arm as well as the forearm segments have significantly different patterns during on water compared to ergometer rowing. These changes specifically affect the “hand-curve” which is the movement of the hand in the sagittal plane of motion. For the movement of the trunk and legs, there were no significant differences between the two types of rowing. Also, Fleming et al. (2014) did observe a greater time for the drive phase for on-water rowing compared to dynamic and stationary ergometer rowing. The average body angles measured at the catch and finish positions of the stroke were statistically similar for both on-water and ergometer rowing (Elliott et al., 2002). The same study found a decreased stroke length during ergometer compared to on-water rowing and cited for this decrease the shorter arm drive in ergometer rowing.

Time to complete the same distance on-water rowing is greater than the time on ergometers with and without a slide (Bazzucchi et al., 2013; de Campos Mello et al., 2009). Yet, some researchers have suggested that a 2,500 m ergometer distance appears

to more closely reflect the effort of on-water rowing (de Campos Mello et al., 2009; Mäestu et al., 2005).

For the kinetic variables, Elliott et al. (2002) concluded that the force curves are similar for on-water rowing and the Rowperfect[®] ergometer. Kleshnev (2008) observed that rowers applied a greater force on the handle while rowing on ergometers compared to rowing on a single scull boat. Researchers observed a faster increase in handle force and leg speed in the boat and on dynamic ergometers compared to stationary ergometers, and attributed these increases to the different magnitude of inertial force needed at the beginning of the drive (Kleshnev, 2008). Overall, on-water rowing technique is considered more multidimensional than ergometer rowing technique because it involves balance, movement dynamics, efficiency and maintenance of the boat speed during the recovery phase (de Campos Mello et al., 2009; Mäestu et al., 2005). Ergometers may be detrimental to on-water rowing technique since the motion of the stroke is not exactly the same for both conditions (Lamb, 1989; Mäestu et al., 2005).

2.6.2 Muscle Activation

Several differences in muscle activity patterns have been observed between on-water rowing and stationary ergometer (Bazzucchi et al., 2013) as well as between stationary ergometer, dynamic ergometer, and on-water rowing (Fleming et al., 2014). Bazzucchi et al. (2013) observed a greater muscle activation on a Concept2[®] ergometer than during on-water rowing, especially for knee extensors. In the other hand, Fleming et al. (2014) found significant differences using iEMG to quantify muscle activation between on-water rowing, stationary ergometer as well as dynamic ergometer. Bazzucchi et al. (2013) observed a difference in terms of timing of maximal activation between stationary ergometer rowing and on-water rowing. The timing difference might be explained by the complexity of the on-water rowing technique (Bazzucchi et al., 2013).

2.6.3 Physiology

On the physiological side, mean and peak oxygen consumption, lactate, mean ventilation as well as peak ventilation were similar for ergometer rowing with and without a slide, as well as on-water rowing. de Campos Mello et al. (2009) observed no statistically

significant difference in heart rate, while Bazzucchi et al. (2013) observed significantly higher heart rate during stationary ergometer rowing. They concluded that ergometer rowing tends to elicit a greater metabolic demand which might be explained by the greater involvement of the arm muscles compared to on-water rowing. Time to complete the test was longer on water than on the ergometer. In the same vein, de Campos Mello et al. (2009) found that there is a similar contribution of the aerobic systems on water compared to rowing on an ergometer when values are normalized to time. Also, Urhausen, Weiler, and Kindermann (1993) observed that blood levels of noradrenaline was significantly higher and adrenaline had a tendency to have higher values while rowing on an ergometer compared to on water rowing at similar heart rates.

2.6.4 Performance

Mikulić et al. (2009) observed a positive correlation between rowers' ergometer performance and World Rowing Championship rankings in 17 of 23 World Championships rowing events. The observed correlations were higher for smaller boats than larger boats. In larger boats, other factors can affect the overall performance such as the synchronization between the individuals when rowing.

Even though there are some biomechanical, physiological and performance differences between ergometer rowing and on-water rowing, ergometers should still be considered valuable tools in testing, cross training and monitoring training (de Campos Mello et al., 2009; Kleshnev, 2008; Mäestu et al., 2005; Mikulić et al., 2009). Nevertheless, data collected on the ergometer still need to be interpreted with judiciousness when used for testing and selection purposes (Kleshnev, 2008).

2.7 Motor Variability in Different Sports

Motor variability has been studied in different sports including cyclic ones. While the emphasis on motor variability in different sport research usually evaluates performance, injuries are also one of the main concerns in these research studies. According to Bartlett et al. (2007), movement variability can be functional and might allow athletes to adapt to their environments, to reduce injury risk, and to facilitate changes in coordination patterns.

Studies have looked at motor variability during a running task in connection with injury. James, Dufek, and Bates (2000) found joint moment variability differed between a healthy and an injury prone group. The injury prone group was determined using a questionnaire and participants had self-reported predisposition for incurring overuse lower extremity injuries. At the maximal vertical jump height, variability of peak ankle joint moment was greater for the injury-prone group. Time to peak variability was greater for the healthy group at 50% of the maximal vertical jump. Also, Hamill et al. (1999) found less variability in lower extremity joint coordination in a symptomatic patellofemoral group compared to healthy individuals. On the other hand, there was no statistical difference between asymptomatic individuals with high Q-angle and low Q-angle. Atanda, Reddy, Rice, and Terry (2009) defined the Q-angle “as the angle between a line drawn from the anterior superior iliac spine to the centre of the patella and a line from the centre of the patella to the tibial tubercle” (p.427). Individuals with a greater Q-angle have a higher risk of lower extremities pain than individuals with a lower Q-angle (de Oliveira Silva et al., 2015).

In running, Wheat, Baltzopoulos, Milner, Bartlett, and Tsaopoulos (2005) studied coordination variability (hip flexion/ knee flexion, hip flexion/ ankle dorsiflexion, knee flexion/ rearfoot inversion) for three conditions including: over ground, treadmill and treadmill-on-demand. While there was no statistically significant difference between the two treadmill conditions, the coordination variability during overground running was greater than on the treadmills.

Hellard et al. (2008) studied stroke rate variability in different swimming styles, different skill levels as well as distances (first 100 m compared to the second 100 m during a 200 m race). Researchers found that the Olympic group had less stroke rate variability than the national group. The variability was greater in the first 100 m compared to the second 100 m for the butterfly, backstroke and freestyle swimming strokes.

Cignetti et al. (2009) observed a larger standard deviation for the angular displacements of the arm and leg at the end of the test compared to the beginning when doing cross-country skiing on a treadmill up to exhaustion. Athletes skied on a treadmill up to

exhaustion at a constant speed and incline. During exhaustion, the increased variability beyond its optimal value might be explained by the neuromuscular system becoming noisier and unstable (Cignetti et al., 2009; Stergiou et al., 2006). In this study, power for both arms and legs decreased throughout the exercise and were negatively correlated with the standard deviation of the normalized time series of the leg and the arm angle.

In wheelchair racing, Wang, Vrongistinos, and Xu (2008) found that consistency in forearm and arm movement patterns is negatively correlated with wheelchair speed and speculated that this variability might be associated with alternately firing different motor units. This variability might also lead to less fatigue by distributing the load across different muscle units.

Preatoni, Ferrario, Donà, Hamill, and Rodano (2010) observed an increase of sample entropy at the hip and ankle joints for skilled and less skilled athletes in race walking. Sample entropy is one of the entropy measures suitable for the analysis of biological signals entropy can be defined as “indices measure the predictability of the signal: the higher the entropy, the less regular and predictable the time series” (Preatoni et al., 2010, p. 1328). Preatoni et al. (2010) determined that sample entropy can be used to characterize more and less skilled individuals.

In basketball, Kudo, Tsutsui, Ishikura, Ito, and Yamamoto (2000) suggested that variable release parameters can result in a consistent throwing performance. This variability is important because it offers greater flexibility to adapt to potential perturbations such as other players (Bartlett et al., 2007).

Variability has been studied in different sports and can have a functional role (Bartlett et al., 2007; Srinivasan & Mathiassen, 2012). It can be associated with performance, injuries, athletic ability and fatigue.

2.8 Motor Variability in Rowing

There are a few studies that mention variability and rowing. While some authors argue that variability is detrimental to rowing performance (Doyle, Lyttle, & Elliott, 2010),

others found that the variability can also have a functional role such as controlling the direction of the boat.

Kleshnev (2012) stated that international crews have a stroke rate variability of 1%, as beginner crews have a stroke rate variability closer to 4-5 %. The stroke rower is the athlete closest to the bow and is the only one who can be seen by all the crew members. This rower sets the pace of the boat and all crew rowers follow their lead. While comparing the crew rowers with the stroke rower, the stroke rower had less variability in the force pattern than the crew rowers. It could be explained because the crew rowers have to coordinate themselves with the stroke rower (Kleshnev, 2012).

Ng, Campbell, Burnett, Smith, and O'Sullivan (2015) found an increased within-subject variability for the lower lumbar angle (angle between the spinous processes of L3, S2, and a vertical line) and upper lumbar angle (angle between the spinous processes of T12, L3, and a vertical line) for participants with low back pain provoked by rowing compared to the participants without pain. The authors suggested that the variability might be the cause or a consequence of the injury. These results are similar to other studies with participants with acute pain such as the ones from Madeleine et al. (2008).

Draper and Smith (2006) found a high consistency of different kinetic rowing variables such as boat velocity, boat acceleration, and pin force. The participants of the study were experienced and rowed 250 m rowing pieces at race stroke rates (Draper & Smith, 2006). Stroke to stroke consistency and propulsive work consistency have been found to be discriminant factors to identify ability levels (Smith & Spinks, 1995). Athletes with more consistency in the previous variables were considered performing better than athletes with less consistency. Doyle et al. (2010) observed a negative correlation between the coefficient of variation of the arm, trunk, handle and seat velocities and average boat velocity. They also suggested that the crews that repeated the same movement pattern consistently tend to row at a higher average boat velocity (Doyle et al., 2010).

Movement variability in rowing has been studied from a kinetic point of view, while only a few studies have looked at kinematic variability, it is possible that kinematic variability has a functional role and allows rowers to adapt to external perturbations.

2.9 Conclusion

This literature review outlined the impact of different factors on motor variability as well as in the sport of rowing. This review also shows the impact of motor variability in other sports, in rowing as well as the impact of the variability in different systems of the human body. Motor variability might prevent overuse injury, while the number of these injuries is significant in rowing. Also, fatigue can affect the rower in different points of view as well as motor variability.

Chapter 3

3 Methods

3.1 Participants

Eleven athletes from the University of Western Ontario Varsity Rowing Team participated in this study. Some background information about the participants was collected (Table 1). All participants signed informed consent forms approved by the institutional Ethics Committee.

Table 1: Background information of the participants

Gender		Age (years)	Rowing category		Performance level	
M	F		Light weight	open	University	National team
4	7	22±2	4	7	7	4

3.2 Testing Procedures

Test pieces

Participants were tested on water at high intensity, and on an ergometer both at high intensity and low intensity. High intensity is the rowing speed used during a long-distance race (4 to 10 km) while low intensity is the speed used for a 60 to 120 minutes of training. Each participant in the study performed all tests. Participants started with the on-water test due to the limited time available. Filming was not possible in the darkness, during rain, or windy conditions. For the on-water part of the study, participants were asked to perform in a single scull boat a 1,750 m or 2,000 m piece at a constant pace and a predetermined high intensity of the rower's long-distance race pace. For the tests on the stationary Concept2[®] ergometer, participants had to perform two 2,000 m pieces at

“high” and “low” intensities. Athletes were given the choice to start their first session with their preferred intensity. Before each test, the rowers went through their individual warm-up routine. The three test sessions were performed on three different days with at least one rest day between the two high intensity pieces.

3.3 Data Collection

Prior to the beginning of each session, customized markers were placed on the participants at different anatomical points on one side of the body. The number of markers and their location depended on the environment (on-water rowing or ergometer rowing). For each participant, markers were placed on the same side of the body throughout all three tests. According to Bartlett, Bussey, and Flyger (2006), movement variability cannot be assessed objectively without markers. The errors stemming from digitizing with the use of surface markers to represent underlying joints are considered small (Bartlett et al., 2006).

3.3.1 On-Water Rowing

One marker was placed on the coronoid process of the ulna (wrist) before the beginning of the test (see Figure 1). Videos were collected at a rate of 30 frames/second with a camera (Sony, Cybershot DSC-RX10M3) perpendicular to the plane of motion that was located at approximately 20 m distance from the rower in a motor boat that travelled parallel to the rowing boat with the speed of the boat. This method was also used in Bechard, Nolte, Kedgley, and Jenkyn (2009). The first set of data was recorded after 200 m into the piece. The second set of data was recorded between 500 m and 200 m before the end of the piece.

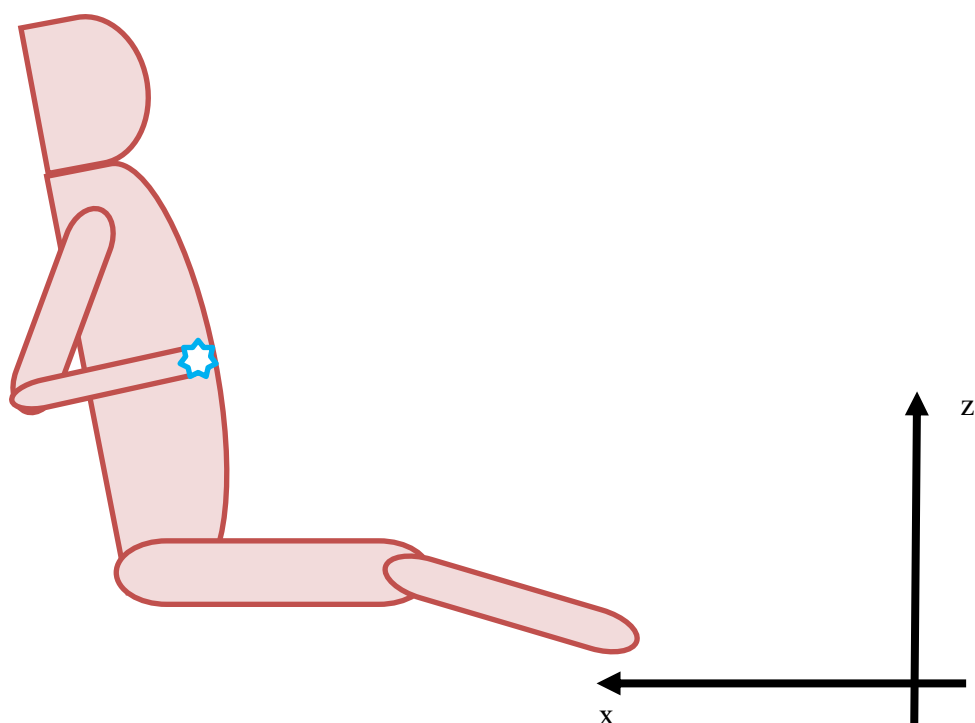



Figure 1: Sketch of a rower in the finish position during a test on the water with the marker () used for this trial.

3.3.2 Ergometer Rowing

Markers were placed on the coronoid process of the ulna (wrist), trochanter major (hip), lateral condyle of the tibia (knee) and lateral malleolus (ankle) before the beginning of each test (see Figure 2). A camera (Sony, Cybershot DSC-RX10M3) was placed perpendicular to the plane of motion on a tripod that was located approximately 5 m away and perpendicular to the plane of motion and recorded at 30 frames/second. The whole 2,000 m piece was recorded.

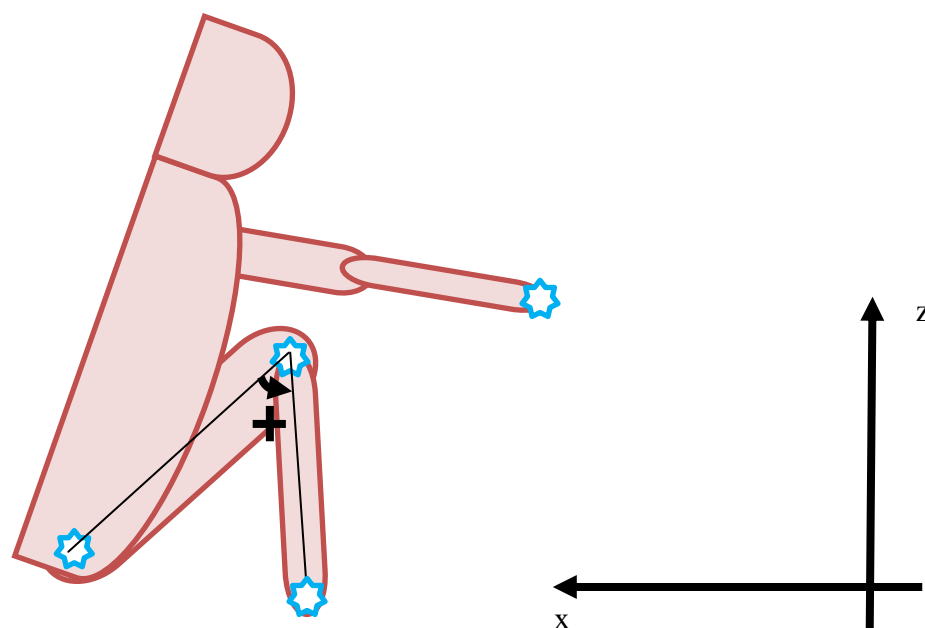



Figure 2: Sketch of a rower in the catch position during a test on the ergometer with the markers () used for this trial

3.4 Data Processing

The videos of the ergometer rowing and on-water rowing were trimmed in order to keep only two videos of 11 consecutive strokes after 200 m and between 500 m and 200 m before the finish for each session.

The number of strokes that is needed to be analyzed for the study was determined using a modified version of the sequential estimation technique (Clarkson, Katch, Kroll, Lane, & Kamen, 1980). In order to calculate a stable variability for each measure, the criterion was met when the cumulative variability fell within the 20-trial standard deviation ± 0.25 of the 20-trial standard deviation. This criterion represented a conservative cut-off and was chosen according to Hamill and McNiven (1990). To find this criterion, this technique was performed for the knee angle and the stroke duration variability on one video per test (high intensity on ergometer, low intensity on ergometer, and high intensity on water). Eleven cycles marked the first time that all the variables fell within the criterion for all conditions.

Digitizing was done using the software Tracker (Douglas Brown, 2018; Version 4.95). Depending on the environment, points digitized included the coronoid process of the

ulna, the trochanter major, lateral condyle of the tibia, the lateral malleolus, a point on the boat as well as the 2 points on the shore. Data were exported into an Excel sheets (Microsoft Excel, 2007) and processed using the software MATLAB (Version 2017a). The raw data associated with the position of the wrist in x-direction relative to the boat was used to determine the catches as presented by Pollock et al. (2012). The frame associated with the catch position was determined by the smallest x-value of the wrist.

3.4.1 On-Water Data

For the on-water analysis, a custom MATLAB program was used to calculate the variability of duration of strokes. Two points on the shoreline which is horizontal in the background of the video were digitized in order to define the x and z-axis of the frame to the movement of the rower. This procedure was done to set a proper coordinate system for every video frame in order to limit possible error coming from the potential turning movements of the camera. The wrist marker as well as a point on the boat were then digitized in order to calculate the coordinates of the wrist marker relative to the boat. This process was needed to be able to compare the data to the ergometer trials and to determine the frame at which the catch occurred. Standard deviation of duration of strokes was used to calculate the temporal variability.

3.4.2 Ergometer Data

A custom MATLAB program was used to calculate variability of knee joint angle in the sagittal plane, as well as the temporal variability of the duration of strokes. Raw data of the markers placed on the greater trochanter, lateral condyle of the tibia and lateral malleolus were filtered using a zero-phase Butterworth filter (order 4). The cut-off frequency of the filter was optimized using the residual analysis technique described in Winter (2009). The angle at the knee joint angle (see Figure 3) was calculated using the law of cosines (Equation 1). The knee joint angle was studied since the majority of the power while rowing is coming from the legs (Kleshnev, 2014).

Equation used to calculate the knee angle (1):

$$\theta_k = \cos^{-1} \frac{((Xh-Xa)^2 + (Zh-Za)^2) - ((Xh-Xk)^2 + (Zh-Zk)^2) - ((Xk-Xa)^2 + (Zk-Za)^2)}{-2 \times (\sqrt{(Xh-Xk)^2 + (Zh-Zk)^2}) \times (\sqrt{(Xk-Xa)^2 + (Zk-Za)^2})} \quad (1)$$

a=ankle, h=hip, k=knee

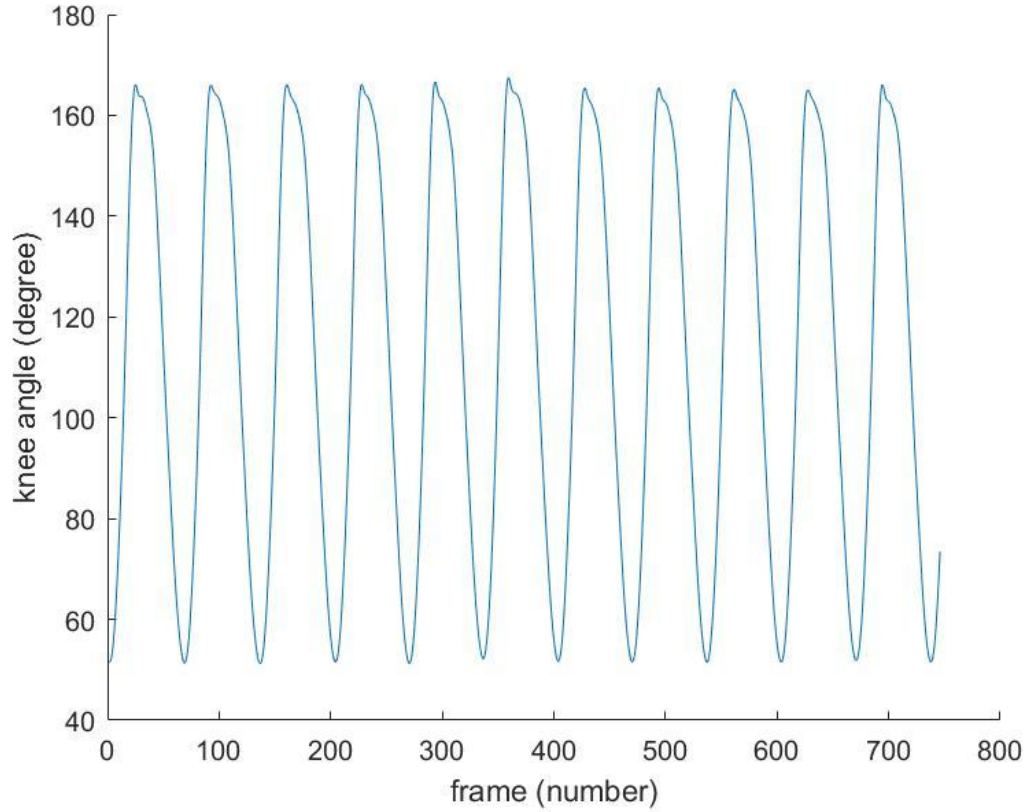


Figure 3: Example of knee angle for 11 strokes

Afterward, time was normalized for each stroke from zero to one hundred percent (Figure 4). Time normalization is used in rowing to allow comparison between strokes and subjects (Pollock et al., 2012).

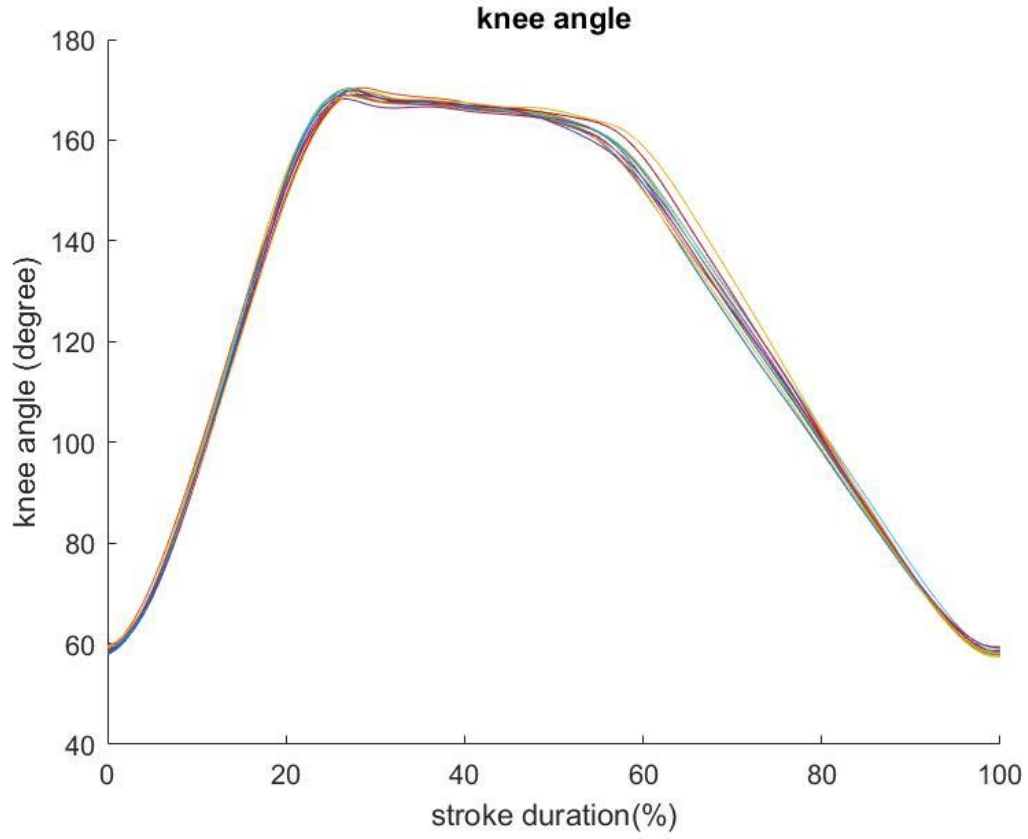


Figure 4: Example of knee angle for 11 strokes normalized with time

For each percent of stroke, standard deviation was calculated for the knee angle (°). The average standard deviation was used to quantify motor variability at each joint. The standard deviation is one of the most used measure of variability (James, 2004).

Average standard deviation was calculated using formula (2) presented by James (2004):

$$SD_{ave} = \left(\frac{\sum_{i=1}^k SD_i^2}{k} \right)^{1/2} \quad (2)$$

The smallest value in x-direction for the wrist was used to determine the catch position for every stroke. The respective time of this position was then used to calculate, the duration of each stroke. Temporal variability of strokes was then calculated using the standard deviation of the duration of all the strokes.

To gather more information about the temporal variability associated with time and intensity, the duration of every stroke during the whole exercise was calculated for both ergometer conditions. It was not possible to include data coming from the on-water analysis since only part of the exercise could be recorded. A rolling window analysis was performed for all stroke duration for both low and high intensity rowing exercises on the ergometer. Each window had 11 strokes. The standard deviation for each window was calculated. The number of strokes was reported as a percentage of the total number of strokes of the whole exercise. This procedure allows the comparison between the different intensities and participants. For each intensity, the median variability of each percent was then calculated.

3.5 Statistical Analysis

Temporal variability and knee joint angle variability have been analyzed separately. The different statistical tests were performed using IBM SPSS Statistic (Version 25).

3.5.1 Temporal Variability

Statistical analysis for the temporal variability was performed using the Generalized estimating equations (GEE) technique. GEE procedure extends the generalized linear model that facilitates the analysis of repeated measurements (Ballinger, 2004). GEE analysis was performed due to the study design not being fully factorial. The working correlation matrix used is independent since the Quasi-likelihood under independence model criterion (QIC) was the smallest (Norusis, 2007). The best model was determined using the lowest Corrected Quasi-likelihood under independence model criterion (QICC) (Norusis, 2007). The predictors used in the model are environment (on water; ergometer), intensity (low and high), and distance (beginning and end). Response variable was the temporal variability (s) and was considered continuous. Due to the number of clusters, the model-based method correlation matrix was used (Horton & Lipsitz, 1999). The Generalized Score Chi-square statistic test was performed (Molenberghs & Verbeke, 2007). The beta coefficient, the *p*-value and the standard error associated with the different predictors in the model will be reported.

3.5.2 Knee Joint Angle Variability

A 2-way ANOVA within subject was performed in order to assess if intensity and distance rowed affect the variability of the knee joint angle. In order to respect the assumptions of normality of the residuals, data were transformed using the reciprocal square root. After the transformation of the data, the normality of residuals was assessed using Kolmogorov Smirnov test and was met for $p > .05$. The assumption regarding the sphericity was tested using Mauchly's test of sphericity and was met for $p > .05$. The p -value as well as the observed power of the distance rowed, the intensity and the interaction between the two factors will be reported.

Chapter 4

4 Results

4.1 Temporal Variability

Due to the low number of clusters and groups, results from this section should be interpreted with caution. Following the statistical analysis, the beta coefficient, the standard error, and the p -value were calculated for each variable included in the model. The environment (on water or ergometer), intensity (low or high) and distance (beginning and end) are factors that are statistically significant in the model. Beta coefficients were calculated for all variables and for the intercept (constant).

Table 2: Beta coefficient, p -value and standard error of the different variables used in the model

Variables	Beta Coefficient	p -value	Standard error
Environment	-0.013	.007 (**)	0.003
Intensity	0.007	.021 (*)	0.003
Distance	0.006	.028(*)	0.0025
Intercept	0.039	.001(**)	0.0025

Using the different factors in the analysis, an equation was associated with the model (Equation 3) to predict the temporal variability of the movement.

$$Y = -0.013 \times X_{environment} + 0.007 \times X_{intensity} + 0.006 \times X_{distance} + 0.039 \quad (3)$$

Where “Y” equals the predicted variability (s), “Xenvironment” (on water =0, ergometer =1), “Xintensity” (high intensity =0, low intensity =1), and “Xdistance” (beginning=1, end=0).

4.2 Effect of Environment on Temporal Variability

Variability of the duration of strokes is affected by the environment ($p=.007$). Variability while rowing on water is greater than the variability while rowing on the ergometer if the other predictors are kept constant (Figure 5). For on-water rowing (high intensity, at the end of the exercise), the predicted variability is 0.039 s while for the ergometer rowing (high intensity, at the end of the exercise) the predicted variability is 0.026 s. On-water rowing increased the variability by 0.013 compared to ergometer rowing.

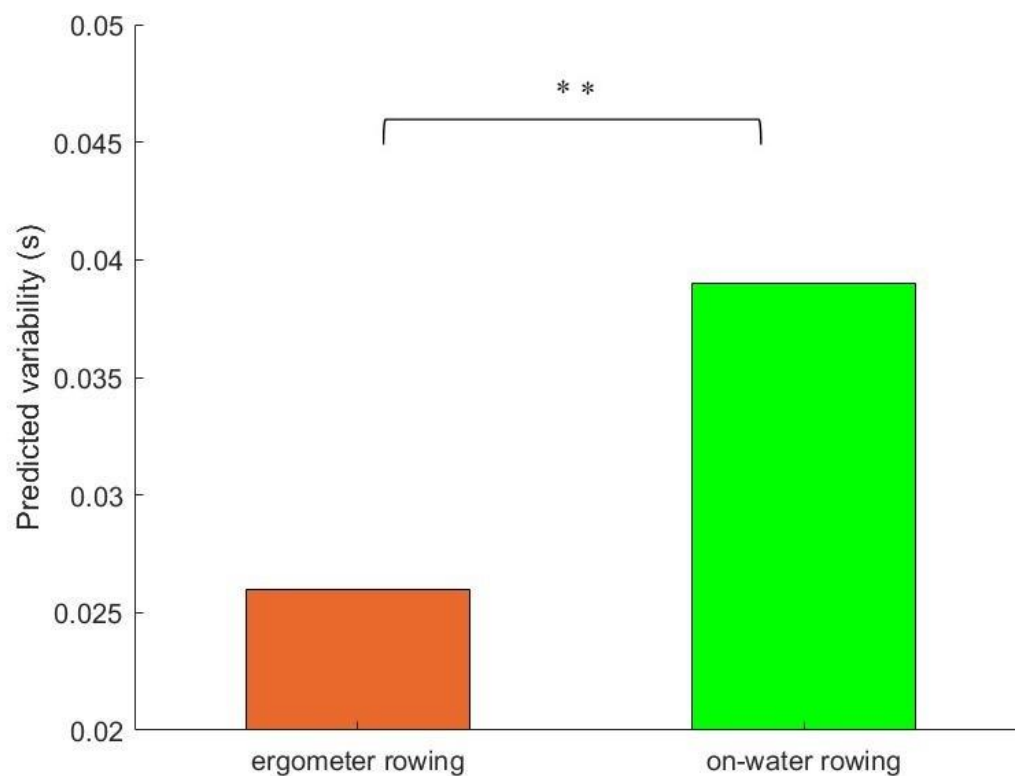


Figure 5: Predicted variability (s) associated with environment at high intensity at the end of the rowing exercise
(** $p \leq .01$)

4.3 Effect of Distance travelled on Temporal Variability

Variability associated with distance is statistically significant in the model ($p=.021$). Predicted variability at the beginning of the rowing exercise (0.033 s) is significantly greater than the variability at the end of the rowing exercise (0.026 s) if rowing on an ergometer at high intensity (see Figure 6).

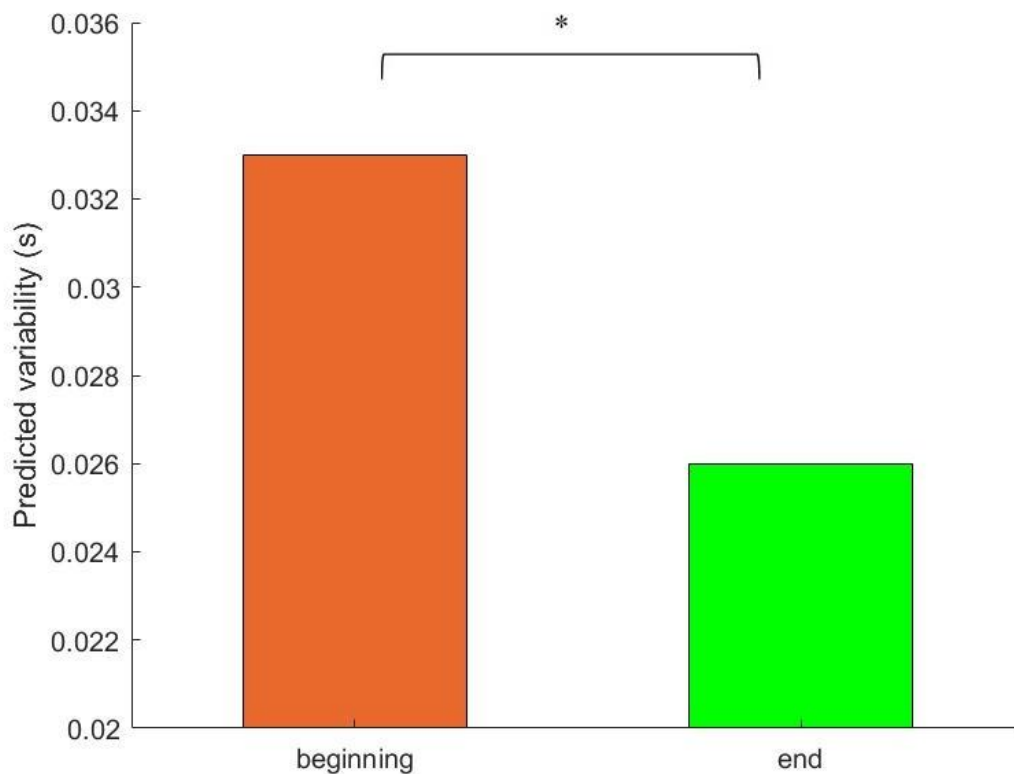


Figure 6: Predicted variability (s) associated with distance at the beginning and end of the rowing exercise at high intensity on the ergometer
(* $p \leq .05$)

4.4 Effect of Intensity on Temporal Variability

There is a statistically significant difference between rowing at low intensity compared to rowing at high intensity (Figure 7). The variability is greater when rowing at low intensity compared to rowing at high intensity if the other predictors are kept constant.

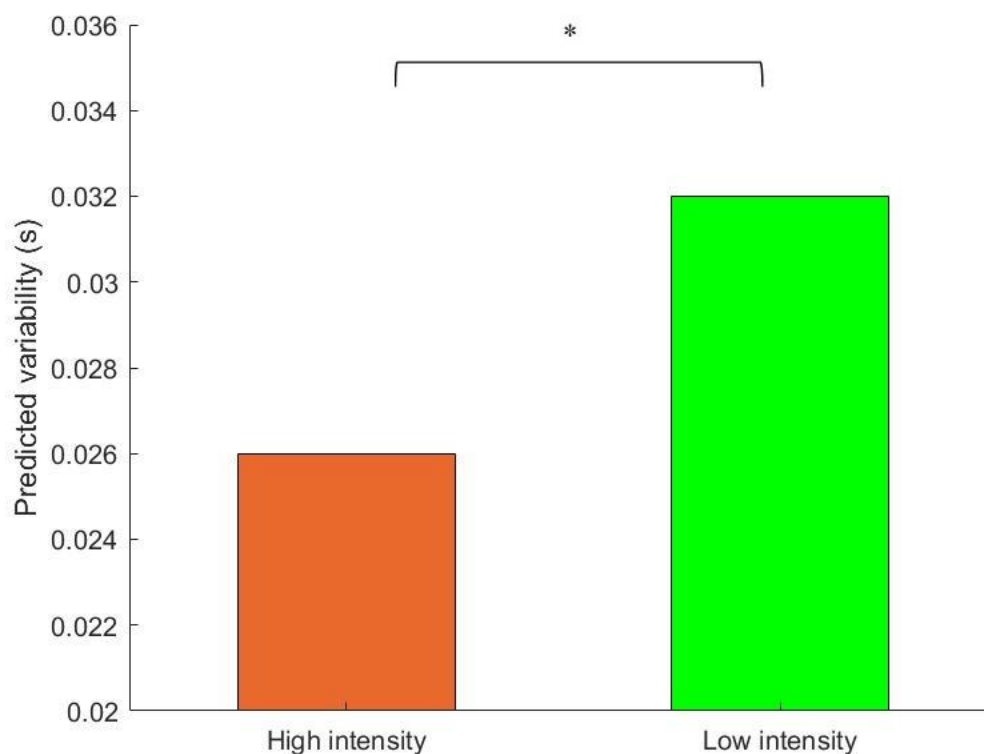


Figure 7: Predicted variability (s) associated with high and low intensity on the ergometer at the end of the rowing exercise
(* $p \leq .05$)

The predicted variability associated with rowing at high intensity on ergometer at the end of the exercise is 0.026 s or 0.032 s if rowing at low intensity.

Temporal variability seems to be greater during most of the rowing exercise (Figure 8).

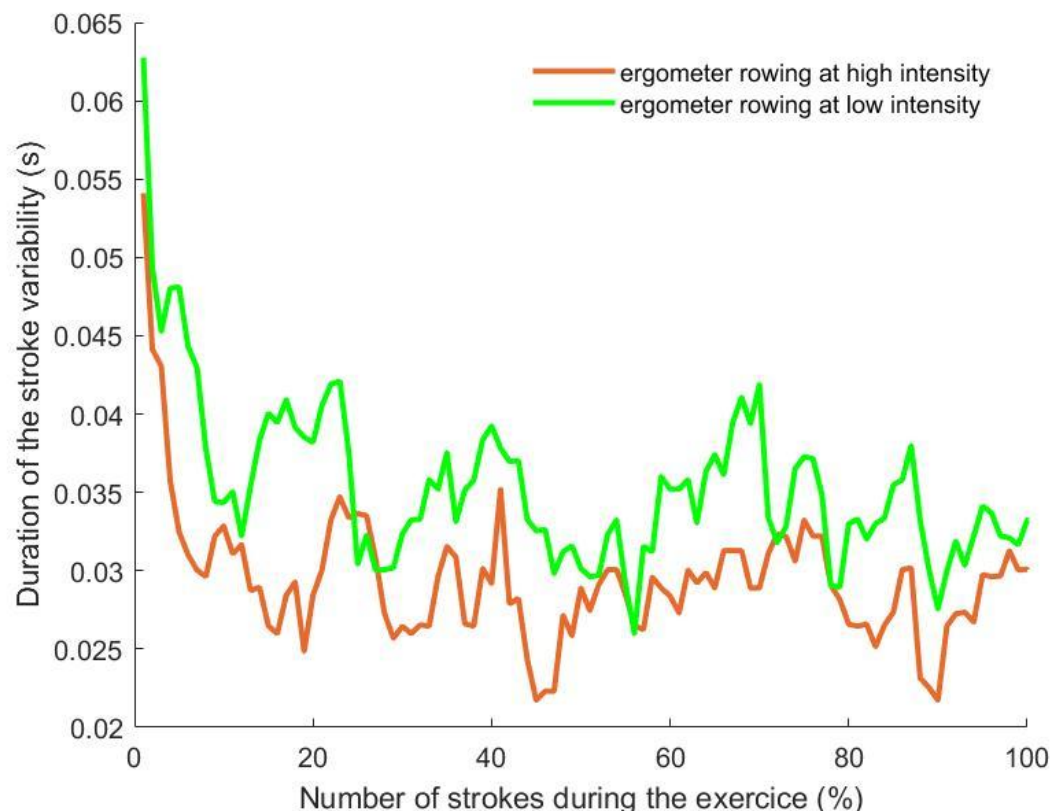


Figure 8: Median of all participants for the duration of stroke variability (s) throughout the whole rowing exercise (Number of strokes during the exercise (%)) for ergometer rowing at high and low intensity

Visual analysis of Figure 8 reveals that the temporal variability associated with the number of strokes during the whole exercise on the ergometer tends to be greater at low intensity compared to rowing at high intensity. The greater variability associated to rowing at a lower intensity is visible for most of the rowing exercise. Also, it seems that there is a greater variability at the beginning of the exercise (0-5%) compared to the rest of the rowing exercise for both intensities. The median variability for each percent of strokes was reported to avoid possible outliers that would greatly affect the central tendency measurement.

4.5 Knee Joint Angle Variability

For the knee joint angle variability, distance, intensity and the interaction between the intensity and the distance were not significantly different (Table 3). The observed power for the different factors and the interaction was considered low (Table 3).

Table 3: Factors and p -Value Associated with the Analysis of Knee Joint Angle Variability

Factors	p -value	Observed power
Intensity	.315	0.16
Distance	.302	0.17
Intensity x Distance	.094	0.38

Following the statistical analysis, results from this section need to be interpreted with caution due to low power.

Chapter 5

5 Discussion

5.1 Stroke Duration Variability Due to the Distance travelled

Temporal variability is greater at the beginning compared to the end of the rowing exercise. In addition, the decrease variability between the beginning and the end of the exercise is not constant.

It is possible that the difference between the variability at the beginning and the end of the exercise is due to the rowers trying to overcome the inertia of the flywheel on the ergometer or the boat to get up to speed and to find the appropriate exercise intensity at the beginning of the exercise, which would increase the variability.

Hellard et al. (2008) observed similar findings as this study. These researchers associated the decrease of temporal variability in swimming to a decrease in speed of the athletes. Although speed was not recorded in this study, participants were asked to row at the same intensity and to be consistent throughout the whole exercise. The participants controlled their intensity with either a monitor in the boat that would provide them with stroke rate and velocity, or with the monitor on the ergometer. Also, even though the task for the athletes was to row with a high intensity, it was not an exhausting intensity since the speed could be sustained for longer than 2,000 m. Therefore, it is unlikely that speed could explain the results of this study.

On the other hand, Cignetti et al. (2009) found that increase in variability was associated with fatigue, and so the decreased variability in this study could be explained by the rowers not rowing to exhaustion, while the participants in Cignetti et al. (2009) skied to exhaustion. In this study, the fatigue might have been substantial enough to have significantly impacted the temporal variability of the rowers. It is also possible that the results may have been different if the first recording of the rowing exercise was taken later in the exercise, as for example at the 300 m mark as opposed to 200 m. The smaller

variability seen at the end of the exercise could possibly point to the relationship between fatigue and injury in rowing.

5.2 Stroke Duration Variability Due to the Environment

There is a greater variability associated with rowing on water compared to rowing on the ergometer. Wheat et al. (2005) found comparable results with a smaller coordination variability when comparing running on the ground and on a treadmill. These researchers suggested that the difference was potentially explained by the surrounding environment being more static while running on a treadmill compared to overground running. Since visual information is important for stability (van Ingen Schenau, 1980), it is possible that the difference of visual information could explain the greater variability associated with running over ground compared to running on a treadmill (Wheat et al., 2005). This theory could also apply to the difference in variability of the duration of strokes between ergometer rowing and on-water rowing. The reference system when rowing on an ergometer is, of course, stable compared to a reference system that moves with the athletes while rowing on water.

Adaptation, one of the functional roles of variability (Bartlett et al., 2007), could also explain the difference of temporal variability between on-water rowing and ergometer rowing. While rowing on water, athletes need to adapt to different factors such as wind and waves, as well as the balance of the boat. It might be possible that the greater variability of the duration of strokes observed on water is due to rowers adapting to these external environmental factors.

Also, since the method of collecting data was not exactly the same between on-water rowing and ergometer rowing, it is possible that the increase in variability due to the environment is in fact due to the data collection. While measurement error contributes to the movement variability, measurement errors from on-water rowing were reduced by adjusting the coordinate system of the camera to the direction of motion.

5.3 Stroke Duration Variability Due to Intensity

There is a greater stroke duration variability at lower intensity compared to higher intensity. These results are in accordance with a study by Jordan, Challis, and Newell (2006). They studied the variability of stride intervals and found that the standard deviation decreased with increased speed while running. Other studies from the same research team have shown a “U-shaped” relationship between stride interval consistency, and walking or running speed (Jordan, Challis, & Newell, 2007; Jordan & Newell, 2008).

Robins, Wheat, Irwin, and Bartlett (2006) have studied the effect of shooting distance on movement variability in basketball. They have found that the greater the distance, the smaller the variability. While a greater distance of shooting is associated with a more difficult task (larger force on the ball, higher velocity of the ball, etc.), it might be possible to think that the decrease in motor variability associated with intensity in rowing can also be explained by the increased difficulty of the task. Robins et al. (2006) attributed the greater variability at closer distances to the larger margin for error and less constrained movement pattern.

5.4 Knee Joint Angle Variability

While intensity and time did not significantly influence knee joint angle variability, there are several possible explanations for it. While rowing on the ergometer, the hip joint and ankle joint are fixed. The ankle is fixed to the foot stretchers while the participants are sitting on a seat that moves on a horizontal beam that is a rail-like guide for the seat wheels. Thus, the movement of the participant's lower extremities is largely constrained, so it is possible that the motor variability is less affected by factors such as intensity and fatigue. Other studies have seen a change in joint angle variability due to fatigue (Cignetti et al., 2009; Selen et al., 2007). The tasks used in these studies have open kinetic chains. Movements with open kinetic chains have more freedom compared to the knee angle joint in rowing, which is considered a closed kinetic chain. This could explain the difference between the results of this study and the other studies mentioned above. In this experiment, low statistical power could also explain the lack of statistical significance for the intensity and distance.

5.5 Limitations

A few potential sources of error could influence the results of this study. Since the method of data collection was not exactly the same for on-water rowing and ergometer rowing, it is difficult to distinguish variability associated with the environment and the variability that is due to the difference in the data acquisition method. The camera was on a static tripod during the ergometer condition while being held by the technician in a moving boat during the on-water condition.

Another possible limitation from this study can arise during the data processing phase. Even with filtering the data and taking great care while digitizing the data to be as accurate as possible, it is possible that experimental error could increase or decrease the variability measured and affect the results of the study.

Due to the difficulty of recruiting highly qualified university and national team rowers to participate in the study, small sample size, power and number of clusters could also influence the results, and the conclusions of the study.

5.6 Conclusion

The results of this study suggested that temporal variability in rowing is influenced by the environment, distance rowed as well as the intensity of the exercise. For the same intensity and distance travelled, a greater variability is demonstrated while rowing on water compared to rowing on the ergometer. These changes could be due to environmental factors such as wind and waves as well as the different information provided by the sight that affects stability. Also, the decreased variability associated with increased intensity might be due to the difficulty of the task or is related to the speed like in running. The change of variability associated with the distance rowed might be explained by fatigue or by the greater variability at the beginning of the exercise to overcome inertia. Variability of the knee joint angle was not affected by the distance and by the intensity. These results could be explained by the closed kinetic chain associated with the knee joint while rowing and by the low statistical power of the study. Rowing coaches should be aware of the different factors influencing variability of the movement

and take them into account when giving feedback to athletes. Also, coaches and athletes should be aware of some functional roles of variability such as adaptation and injury prevention.

5.7 Future Research

This study was interested in factors influencing variability such as environment, distance and intensity. It would be interesting to compare the variability of kinetic variables, such as force, to variability of kinematical variables, such as stroke duration variability or joint angle variability. This would allow a better understanding of the relationship between these two types of measurements. Also, it would be interesting to see how crew rowing would impact the variability of individual rowers.

Another subject of interest would be to study variability associated with potential injuries in rowing. Larger variability of the movement could possibly reduce the stress on tissues, which may decrease the number of injuries. It would be interesting to better understand if this theory could apply to rowing since most injuries in rowing are often due to the repetitive nature of the sport (Hosea & Hannafin, 2012).

Bibliography

- Atanda, A., Reddy, D., Rice, J. A., & Terry, M. A. (2009). Injuries and Chronic Conditions of the Knee in Young Athletes. *Pediatrics in Review*, 30(11), 419-430.
- Aune, T. K., Ingvaldsen, R. P., & Ettema, G. J. C. (2008). Effect of Physical Fatigue on Motor Control at Different Skill Levels. *Perceptual and Motor Skills*, 106(2), 371-386.
- Babloyantz, A., & Destexhe, A. (1986). Low-Dimensional Chaos in an Instance of Epilepsy. *Proceedings of the National Academy of Sciences*, 83(10), 3513-3517.
- Ballinger, G. A. (2004). Using Generalized Estimating Equations for Longitudinal Data Analysis. *Organizational Research Methods*, 7(2), 127-150.
- Bartlett, R. M., Wheat, J., & Robins, M. (2007). Is Movement Variability Important for Sports Biomechanists? *Sports Biomechanics*, 6(2), 224-243.
- Baudouin, A., & Hawkins, D. (2004). Investigation of Biomechanical Factors Affecting Rowing Performance. *Journal of Biomechanics*, 37(7), 969-976.
- Bazzucchi, I., Sbriccoli, P., Nicolò, A., Passerini, A., Quinzi, F., Felici, F., & Sacchetti, M. (2013). Cardio-Respiratory and Electromyographic Responses to Ergometer and on-Water Rowing in Elite Rowers. *European Journal of Applied Physiology*, 113(5), 1271-1277.
- Bechard, D. J., Nolte, V., Kedgley, A. E., & Jenkyn, T. R. (2009). Total Kinetic Energy Production of Body Segments Is Different between Racing and Training Paces in Elite Olympic Rowers. *Sports Biomechanics*, 8(3), 199-211.
- Beggs, V., Nolte, V., & Dickey, J. (2016). The Impact of Nutritional Counseling in Conjunction with Co-Active Coaching on Behavior Change of Varsity Female Rowers. *Sports Nutrition Therapy*, 1(112), 1-8.
- Benson, A., Abendroth, J., King, D., & Swensen, T. (2011). Comparison of Rowing on a Concept 2 Stationary and Dynamic Ergometer. *Journal of Sports Science & Medicine*, 10(2), 267-273.
- Blake, T. A., McKay, C. D., Meeuwisse, W. H., & Emery, C. A. (2016). The Impact of Concussion on Cardiac Autonomic Function: A Systematic Review. *Brain injury*, 30(2), 132-145.
- Cignetti, F., Schena, F., & Rouard, A. (2009). Effects of Fatigue on Inter-Cycle Variability in Cross-Country Skiing. *Journal of Biomechanics*, 42(10), 1452-1459.

- Clarkson, P. M., Katch, F. I., Kroll, W., Lane, R., & Kamen, G. (1980). Regional Adipose Cellularity and Reliability of Adipose Cell Size Determination. *The American Journal of Clinical Nutrition*, 33(11), 2245-2252.
- Cortes, N., Onate, J., & Morrison, S. (2014). Differential Effects of Fatigue on Movement Variability. *Gait & Posture*, 39(3), 888-893.
- Côté, J. N., Raymond, D., Mathieu, P. A., Feldman, A. G., & Levin, M. F. (2005). Differences in Multi-Joint Kinematic Patterns of Repetitive Hammering in Healthy, Fatigued and Shoulder-Injured Individuals. *Clinical Biomechanics*, 20(6), 581-590.
- de Campos Mello, F., de Moraes Bertuzzi, R. C., Grangeiro, P. M., & Franchini, E. (2009). Energy Systems Contributions in 2,000 m Race Simulation: A Comparison among Rowing Ergometers and Water. *European Journal of Applied Physiology*, 107(5), 615-619.
- de Oliveira Silva, D., Briani, R. V., Pazzinatto, M. F., Gonçalves, A. V., Ferrari, D., Aragão, F. A., & de Azevedo, F. M. (2015). Q-Angle Static or Dynamic Measurements, Which Is the Best Choice for Patellofemoral Pain? *Clinical Biomechanics*, 30(10), 1083-1087.
- Dekker, J. M., Schouten, E. G., Klootwijk, P., Pool, J., Swenne, C. A., & Kromhout, D. (1997). Heart Rate Variability from Short Electrocardiographic Recordings Predicts Mortality from All Causes in Middle-Aged and Elderly Men: The Zutphen Study. *American Journal of Epidemiology*, 145(10), 899-908.
- Doyle, M., Lyttle, A., & Elliott, B. (2010, July). *The Consistency of Force and Movement Variables as an Indicator of Rowing Performance*. In R. Jensen, W. Ebben, E. Petushek, C. Richter & K. Roemer (Eds.): Proceedings of the 28 International Conference on Biomechanics in Sports, Marquette, United States, July 19-23, 2010.
- Draper, C., & Smith, R. (2006). *Consistency of Technical and Performance Based Rowing Variables in Single Sculling*. In H. Schwameder, G. Strutzenberger, V. Fastenbauer, S. Lindinger, E. Müller (Eds.): Proceedings of the 24 International Symposium on Biomechanics in Sports, Salzburg, Austria, July 14-18, 2006.
- Elliott, B., Lyttle, A., & Birkett, O. (2002). Rowing: The Rowperfect Ergometer: A Training Aid for on-Water Single Scull Rowing. *Sports Biomechanics*, 1(2), 123-134.
- Enoka, R., & Stuart, D. (1985). The Contribution of Neuroscience to Exercise Studies. *Federation Proceedings*, 44(7), 2279-2285.
- Evans, G., & Redgrave, A. (2016a). Great Britain Rowing Team Guideline for Diagnosis and Management of Rib Stress Injury: Part 1. *British Journal of Sports Medicine*, 50(5), 266-269.

- Evans, G., & Redgrave, A. (2016b). Great Britain Rowing Team Guideline for Diagnosis and Management of Rib Stress Injury: Part 2 – the Guideline Itself. *British Journal of Sports Medicine*, 50(5), 270-272.
- Fleming, N., Donne, B., & Mahony, N. (2014). A Comparison of Electromyography and Stroke Kinematics During Ergometer and on-Water Rowing. *Journal of Sports Sciences*, 32(12), 1127-1138.
- Frias, M. A., Virzi, J., Golaz, O., Gencer, B., Mach, F., & Vuilleumier, N. (2018). Impact of Long Distance Rowing on Biological Health: A Pilot Study. *Clinical Biochemistry*, 53, 142-147.
- Friedman, J., & Friedman, H. (1993). Fatigue in Parkinson's Disease. *Neurology*, 43(10), 2016-2018.
- Fuller, J. R., Fung, J., & Côté, J. N. (2011). Time-Dependent Adaptations to Posture and Movement Characteristics During the Development of Repetitive Reaching Induced Fatigue. *Experimental Brain Research*, 211(1), 133-143.
- Gallagher, K. M., Nelson-Wong, E., & Callaghan, J. P. (2011). Do Individuals Who Develop Transient Low Back Pain Exhibit Different Postural Changes Than Non-Pain Developers During Prolonged Standing? *Gait & Posture*, 34(4), 490-495.
- Gallez, D., & Babloyantz, A. (1991). Predictability of Human Eeg: A Dynamical Approach. *Biological Cybernetics*, 64(5), 381-391.
- Gates, D. H., & Dingwell, J. B. (2011). The Effects of Muscle Fatigue and Movement Height on Movement Stability and Variability. *Experimental Brain Research*, 209(4), 525-536.
- Georgoulis, A. D., Moraiti, C., Ristanis, S., & Stergiou, N. (2006). A Novel Approach to Measure Variability in the Anterior Cruciate Ligament Deficient Knee During Walking: The Use of the Approximate Entropy in Orthopaedics. *Journal of Clinical Monitoring and Computing*, 20(1), 11-18.
- Hamill, J., & McNiven, S. L. (1990). Reliability of Selected Ground Reaction Force Parameters During Walking. *Human Movement Science*, 9(2), 117-131.
- Hamill, J., van Emmerik, R. E., Heiderscheit, B. C., & Li, L. (1999). A Dynamical Systems Approach to Lower Extremity Running Injuries. *Clinical Biomechanics*, 14(5), 297-308.
- Heiderscheit, B. C., Hamill, J., & van Emmerik, R. E. A. (2002). Variability of Stride Characteristics and Joint Coordination among Individuals with Unilateral Patellofemoral Pain. *Journal of Applied Biomechanics*, 18(2), 110-121.
- Hellard, P., Dekerle, J., Avalos, M., Caudal, N., Knopp, M., & Hauswirth, C. (2008). Kinematic Measures and Stroke Rate Variability in Elite Female 200-m

- Swimmers in the Four Swimming Techniques: Athens 2004 Olympic Semi-Finalists and French National 2004 Championship Semi-Finalists. *Journal of Sports Sciences*, 26(1), 35-46.
- Hill, H. (2002). Dynamics of Coordination within Elite Rowing Crews: Evidence from Force Pattern Analysis. *Journal of Sports Sciences*, 20(2), 101-117.
- Holt, P. J. E., Bull, A. M. J., Cashman, P. M. M., & McGregor, A. H. (2003). Kinematics of Spinal Motion During Prolonged Rowing. *International Journal of Sports Medicine*, 24(8), 597-602.
- Hooper, I., Blanch, P., & Sternfeldt, J. (2011). The Development of a Clinical Management Pathway for Chest Wall Pain in Elite Rowers. *Journal of Science and Medicine in Sport*, 14, e104.
- Horton, N. J., & Lipsitz, S. R. (1999). Review of Software to Fit Generalized Estimating Equation Regression Models. *The American Statistician*, 53(2), 160-169.
- Hosea, T. M., & Hannafin, J. A. (2012). Rowing Injuries. *Sports Health*, 4(3), 236-245.
- Husmann, F., Gube, M., Felser, S., Weippert, M., Mau-Moeller, A., Bruhn, S., & Behrens, M. (2017). Central Factors Contribute to Knee Extensor Strength Loss after 2000-m Rowing in Elite Male and Female Rowers. *Medicine and Science in Sports and Exercise*, 49(3), 440-449.
- James, C. R. (2004). Considerations of Movement Variability in Biomechanics Research. In N. Stergiou (Ed.), *Innovative Analyses of Human Movement* (pp. 29-62). Champaign, IL: Human Kinetics.
- James, C. R., Dufek, J. S., & Bates, B. T. (2000). Effects of Injury Proneness and Task Difficulty on Joint Kinetic Variability. *Medicine and Science in Sports and Exercise*, 32(11), 1833-1844.
- Jordan, K., Challis, J. H., & Newell, K. M. (2006). Long Range Correlations in the Stride Interval of Running. *Gait & Posture*, 24(1), 120-125.
- Jordan, K., Challis, J. H., & Newell, K. M. (2007). Walking Speed Influences on Gait Cycle Variability. *Gait & Posture*, 26(1), 128-134.
- Jordan, K., & Newell, K. M. (2008). The Structure of Variability in Human Walking and Running Is Speed-Dependent. *Exercise and Sport Sciences Reviews*, 36(4), 200-204.
- Kajaia, T., Maskhulia, L., Chelidze, K., Akhalkatsi, V., & Kakhabrishvili, Z. (2017). The Effects of Non-Functional Overreaching and Overtraining on Autonomic Nervous System Function in Highly Trained Georgian Athletes. *Georgian Medical News*, 3(264), 97-103.

- Karlson, K. A. (1998). Rib Stress Fractures in Elite Rowers. *The American Journal of Sports Medicine*, 26(4), 516-519.
- Kleshnev, V. (2008, August). *Comparison of on-Water Rowing with Its Simulation on Concept2 and Rowperfect Machines*. In Q. Wang (Ed): Proceedings of the 23 International Symposium on Biomechanics in Sports, Beijing, China, August 22-27, 2005.
- Kleshnev, V. (2012). Stability and Variability of Rower's Motions. Retrieved from <http://www.biorow.com>
- Kleshnev, V. (2014). Amplitude and Power of Body Segments. Retrieved from <http://www.biorow.com>
- Kudo, K., Tsutsui, S., Ishikura, T., Ito, T., & Yamamoto, Y. (2000). Compensatory Coordination of Release Parameters in a Throwing Task. *Journal of Motor Behavior*, 32(4), 337-345.
- Lamb, D. H. (1989). A Kinematic Comparison of Ergometer and on-Water Rowing. *The American Journal of Sports Medicine*, 17(3), 367-373.
- Lamoth, C. J. C., Meijer, O. G., Daffertshofer, A., Wuisman, P. I. J. M., & Beek, P. J. (2006). Effects of Chronic Low Back Pain on Trunk Coordination and Back Muscle Activity During Walking: Changes in Motor Control. *European Spine Journal*, 15(1), 23-40.
- Lomond, K. V., & Côté, J. N. (2010). Movement Timing and Reach to Reach Variability During a Repetitive Reaching Task in Persons with Chronic Neck/Shoulder Pain and Healthy Subjects. *Experimental Brain Research*, 206(3), 271-282.
- Mackenzie, H. A., Bull, A. M., & McGregor, A. H. (2008). Changes in Rowing Technique over a Routine One Hour Low Intensity High Volume Training Session. *Journal of Sports Science & Medicine*, 7(4), 486-491.
- Madeleine, P., & Madsen, T. (2009). Changes in the Amount and Structure of Motor Variability During a Deboning Process Are Associated with Work Experience and Neck-Shoulder Discomfort. *Applied Ergonomics*, 40(5), 887-894.
- Madeleine, P., Mathiassen, S. E., & Arendt-Nielsen, L. (2008). Changes in the Degree of Motor Variability Associated with Experimental and Chronic Neck-Shoulder Pain During a Standardised Repetitive Arm Movement. *Experimental Brain Research*, 185(4), 689-698.
- Mäestu, J., Jürimäe, J., & Jürimäe, T. (2005). Monitoring of Performance and Training in Rowing. *Sports Medicine*, 35(7), 597-617.
- Malik, M. (1998). Heart Rate Variability. *Current Opinion in Cardiology*, 13(1), 36-44.

- Martindale, W. O., & Robertson, D. G. E. (1984). Mechanical Energy in Sculling and in Rowing an Ergometer. *Canadian Journal of Applied Sport Sciences*, 9(3), 153-163.
- Maselli, F., Ciuro, A., Mastrosimone, R., Cannone, M., Nicoli, P., Signori, A., & Testa, M. (2015). Low Back Pain among Italian Rowers: A Cross-Sectional Survey. *Journal of Back and Musculoskeletal Rehabilitation*, 28(2), 365-376.
- Mbourou, G. A., Lajoie, Y., & Teasdale, N. (2003). Step Length Variability at Gait Initiation in Elderly Fallers and Non-Fallers, and Young Adults. *Gerontology*, 49(1), 21-26.
- McDonnell, L. K., Hume, P. A., & Nolte, V. (2011). Rib Stress Fractures among Rowers. *Sports Medicine*, 41(11), 883-901.
- Mikulić, P., Smoljanović, T., Bojanić, I., Hannafin, J. A., & Matković, B. R. (2009). Relationship between 2000-m Rowing Ergometer Performance Times and World Rowing Championships Rankings in Elite-Standard Rowers. *Journal of Sports Sciences*, 27(9), 907-913.
- Molenberghs, G., & Verbeke, G. (2007). Likelihood Ratio, Score, and Wald Tests in a Constrained Parameter Space. *The American Statistician*, 61(1), 22-27.
- Moseley, G. L., & Hodges, P. W. (2006). Reduced Variability of Postural Strategy Prevents Normalization of Motor Changes Induced by Back Pain: A Risk Factor for Chronic Trouble? *Behavioral Neuroscience*, 120(2), 474-476.
- Newell, K. M., & Corcos, D.M. (1993). Issues in Variability and Motor Control. In K. M. Newell. & D. M. Corcos (Eds.), *Variability and Motor Control* (pp. 1-12). Champaign, IL: Human Kinetics Publishers, Inc.
- Ng, L., Campbell, A., Burnett, A., Smith, A., & O'Sullivan, P. (2015). Spinal Kinematics of Adolescent Male Rowers with Back Pain in Comparison with Matched Controls During Ergometer Rowing. *Journal of Applied Biomechanics*, 31(6), 459-468.
- Ng, L., Perich, D., Burnett, A., Campbell, A., & O'Sullivan, P. (2014). Self-Reported Prevalence, Pain Intensity and Risk Factors of Low Back Pain in Adolescent Rowers. *Journal of Science and Medicine in Sport*, 17(3), 266-270.
- Norusis, M. (2007). *SPSS 15.0 Advanced Statistical Procedures Companion*. Chicago, IL: Prentice Hall Inc.
- Plews, D. J., Laursen, P. B., Kilding, A. E., & Buchheit, M. (2012). Heart Rate Variability in Elite Triathletes, Is Variation in Variability the Key to Effective Training? A Case Comparison. *European Journal Applied Physiology*, 112(11), 3729-3741.

- Plews, D. J., Laursen, P. B., Kilding, A. E., & Buchheit, M. (2014). Heart-Rate Variability and Training-Intensity Distribution in Elite Rowers. *International Journal of Sports Physiology and Performance*, 9(6), 1026-1032.
- Pollock, C. L., Jones, I. C., Jenkyn, T. R., Ivanova, T. D., & Garland, S. J. (2012). Changes in Kinematics and Trunk Electromyography During a 2000 m Race Simulation in Elite Female Rowers. *Scandinavian Journal of Medicine & Science in Sports*, 22(4), 478-487.
- Preatoni, E., Ferrario, M., Donà, G., Hamill, J., & Rodano, R. (2010). Motor Variability in Sports: A Non-Linear Analysis of Race Walking. *Journal of Sports Sciences*, 28(12), 1327-1336.
- Qin, J., Lin, J.-H., Faber, G. S., Buchholz, B., & Xu, X. (2014). Upper Extremity Kinematic and Kinetic Adaptations During a Fatiguing Repetitive Task. *Journal of Electromyography and Kinesiology*, 24(3), 404-411.
- Rachnavy, P. (2012). Rowing Biomechanics and Injury Prevention. *Journal of Science and Medicine in Sport*, 15, S132.
- Robins, R., Wheat, J., Irwin, G., & Bartlett, R. M. (2006). The Effect of Shooting Distance on Movement Variability in Basketball. *Journal of Human Movement Studies*, 50(4), 217-238.
- Rowing Canada. (n.d.). *Coxswains*. Retrieved from <http://rowingcanada.org/sites/default/files/coxswains.pdf>
- Rumball, J. S., Lebrun, C. M., Di Ciacca, S. R., & Orlando, K. (2005). Rowing Injuries. *Sports Medicine*, 35(6), 537-555.
- Seifert, L., Lardy, J., Bourbousson, J., Adé, D., Nordez, A., Thouvarecq, R., & Saury, J. (2017). Interpersonal Coordination and Individual Organization Combined with Shared Phenomenological Experience in Rowing Performance: Two Case Studies. *Frontiers in Psychology*, 8(75), 1-21.
- Selen, L. P. J., Beek, P. J., & van Dieën, J. H. (2007). Fatigue-Induced Changes of Impedance and Performance in Target Tracking. *Experimental Brain Research*, 181(1), 99-108.
- Smith, R. M., & Spinks, W. L. (1995). Discriminant Analysis of Biomechanical Differences between Novice, Good and Elite Rowers. *Journal of Sports Sciences*, 13(5), 377-385.
- Smoljanovic, T., Bohacek, I., Hannafin, J. A., Terborg, O., Hren, D., Pecina, M., & Bojanic, I. (2015). Acute and Chronic Injuries among Senior International Rowers: A Cross-Sectional Study. *International Orthopaedics*, 39(8), 1623-1630.

- Srinivasan, D., & Mathiassen, S. E. (2012). Motor Variability in Occupational Health and Performance. *Clinical Biomechanics*, 27(10), 979-993.
- Stam, K. J., Tavy, D. L. J., Jelles, B., Achtereekte, H. A. M., Slaets, J. P. J., & Keunen, R. W. M. (1994). Non-Linear Dynamical Analysis of Multichannel Eeg: Clinical Applications in Dementia and Parkinson's Disease. *Brain Topography*, 7(2), 141-150.
- Stergiou, N., Harbourne, R. T., & Cavanaugh, J. T. (2006). Optimal Movement Variability: A New Theoretical Perspective for Neurologic Physical Therapy. *Journal of Neurologic Physical Therapy*, 30(3), 120-129.
- Sterling, M., Jull, G., & Wright, A. (2001). The Effect of Musculoskeletal Pain on Motor Activity and Control. *The Journal of Pain*, 2(3), 135-145.
- Thornton, J. S., Vinther, A., Wilson, F., Lebrun, C. M., Wilkinson, M., Di Ciacca, S. R., . . . Smoljanovic, T. (2017). Rowing Injuries: An Updated Review. *Sports Medicine*, 47(4), 641-661.
- Urhausen, A., Weiler, B., & Kindermann, W. (1993). Heart Rate, Blood Lactate, and Catecholamines During Ergometer and on Water Rowing. *International Journal of Sports Medicine*, 14(S 1), S20-S23.
- van den Hoorn, W., Bruijn, S. M., Meijer, O. G., Hodges, P. W., & van Dieën, J. H. (2012). Mechanical Coupling between Transverse Plane Pelvis and Thorax Rotations During Gait Is Higher in People with Low Back Pain. *Journal of Biomechanics*, 45(2), 342-347.
- van Ingen Schenau, G. J. (1980). Some Fundamental Aspects of the Biomechanics of Overground Versus Treadmill Locomotion. *Medicine and Science in Sports and Exercise*, 12(4), 257-261.
- Vinther, A., & Thornton, J. S. (2016). Management of Rib Pain in Rowers: Emerging Issues. *British Journal of Sports Medicine*, 50(3), 141-142.
- Wang, Y. T., Vrongistinos, K. D., & Xu, D. (2008). The Relationship between Consistency of Propulsive Cycles and Maximum Angular Velocity During Wheelchair Racing. *Journal of Applied Biomechanics*, 24(3), 280-287.
- Wheat, J. S., Baltzopoulos, V., Milner, C. E., Bartlett, R. M., & Tsaopoulos, D. (2005). *Coordination Variability During Overground, Treadmill and Treadmill-on-Demand Running*. In Q. Wang (ed.): *Proceedings of the 23th International Symposium on Biomechanics in sports*, Beijing, China, August 22-27, 2005.

- Wilson, F., Gissane, C., Gormley, J., & Simms, C. (2008). A 12 Month Prospective Cohort Study of Injury in International Rowers. *British Journal of Sports Medicine*.
- Wilson, F., Gissane, C., & McGregor, A. (2014). Ergometer Training Volume and Previous Injury Predict Back Pain in Rowing; Strategies for Injury Prevention and Rehabilitation. *British Journal of Sports Medicine*, 48(21), 1534-1537.
- Wilson, F., Simms, C., Gormley, J., & Gissane, C. (2011). Kinematics of Lumbar Spine Motion in Rowing During a Fatiguing Protocol: A Comparison of Ergometer and Boat Rowing. *British Journal of Sports Medicine*, 45(4), 383.
- Winter, D. A. (2009). *Biomechanics and Motor Control of Human Movement* (4 ed.). Hoboken, NJ: John Wiley & Sons.
- World Rowing. (n.d.-a). *About Fisa*. Retrieved from <http://www.worldrowing.com/fisa/>
- World Rowing. (n.d.-b). *Events*. Retrieved from <http://www.worldrowing.com/events/>

Appendix 1



Research Ethics

Western University Health Science Research Ethics Board HSREB Delegated Initial Approval Notice

Principal Investigator: Dr. Volker Nolte
Department & Institution: Health Sciences\Kinesiology, Western University

Review Type: Delegated
HSREB File Number: 109181
Study Title: Motor variability related to fatigue and potential injury in rowing

HSREB Initial Approval Date: May 26, 2017
HSREB Expiry Date: May 26, 2018

Documents Approved and/or Received for Information:

Document Name	Comments	Version Date
Western University Protocol		2017/05/23
Letter of Information & Consent		2017/05/23
Instruments	PAR-Q questionnaire	2017/03/22

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above named study, as of the HSREB Initial Approval Date noted above.

HSREB approval for this study remains valid until the HSREB Expiry Date noted above, conditional to timely submission and acceptance of HSREB Continuing Ethics Review.

The Western University HSREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the International Conference on Harmonization of Technical Requirements for Registration of Pharmaceuticals for Human Use Guideline for Good Clinical Practice Practices (ICH E6 R1), the Ontario Personal Health Information Protection Act (PHIPA, 2004), Part 4 of the Natural Health Product Regulations, Health Canada Medical Device Regulations and Part C, Division 5, of the Food and Drug Regulations of Health Canada.

Members of the HSREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB.

The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.



Western University, Research, Support Services Bldg., Rm. 5150
London, ON, Canada N6G 1G9 t. 519.661.3036 f. 519.850.2466 www.uwo.ca/research/ethics

Curriculum Vitae

Name:	Maude Potvin-Gilbert
Post-secondary Education and Degrees:	<p>Université Laval Quebec City, Qc, Canada 2011-2016 BSc.</p> <p>The University of Western Ontario London, Ontario, Canada 2016-2018 MSc.</p>
Honours and Awards:	<p>The University of Western Ontario, Kinesiology Travel Award (2018)</p> <p>The University of Western Ontario, Graduate Student Conference Travel Award (2018)</p> <p>Province of Ontario Graduate Scholarship (2017-2018)</p> <p>Schmeelk Canada Foundation Fellowship (2017-2018)</p> <p>Bourse du CIRRIIS (2016)</p> <p>Prix de la concentration : Concentration préparation Physique et performance sportive (2016)</p>
Related Work Experience	<p>Teaching Assistant The University of Western Ontario 2016-2017</p>
Presentations:	<p>Ontario Biomechanics Conference 2018 Poster presentation</p> <p>Kinesiology Graduate Student Association Symposium 2017 Poster presentation</p> <p>Sport Innovation Summit 2016 and 2017 Poster Presentation</p>

Journée synthèse des étudiants d'été du CIRRS 2017
Oral presentation

Journée de la santé de la faculté de médecine de
l'Université Laval 2017
Poster Presentation